Synthesis, Characterization and Prognostic Modeling of Functionally Graded Hybrid Composites for Extreme Environments

Principal Investigator

Dimitris C. Lagoudas

Department of Aerospace Engineering

Texas A&M University

College Station, TX 77843

Participating Universities

Texas A&M University

University of Illinois at Urbana-Champaign

Virginia Polytechnic Institute and State University

Stanford University

University of Dayton Research Institute

MURI Goals

A comprehensive research program coupling thermal-mechanical-acoustic flight loads to guide the design of multi-functional Functionally Graded Hybrid Composite (FGHC) systems with integrated sensing capabilities for extreme environments.

- Develop a novel hybrid ceramic/metal/polymer composite for high-temperature multifunctional aerospace applications through integrated multiscale characterization and modeling approaches.

- Incorporate integrated sensing capabilities for structural health monitoring.

- Target operating environment: 250 °C - 1000 °C, with a durability envelope of 1000 hours exposure at 550 °C and 300 thermal cycles.

MURI Faculty Team

TAMU

Cizmas
Gao
Karaman
Lagoudas
Ochoa
Ounaies
Radovic
Reddy
Whitcomb

UIUC

Guebelle
Sottos
White

VaTech

Goulbourne
Inman
Seidel

Stanford

Chang

UDRI

Lafdi

Research Thrusts

1. Development and Fabrication

- Develop a multifunctional functionally graded hybrid composite (FGHC) with multiple layers: a ceramic thermal barrier layer, a graded ceramic/ metal composite (GCMeC) layer and a high-temperature polymer matrix composite (PMC).

2. Multiscale Characterization

- Apply experimental techniques to obtain mechanical and physical properties of GCMeC and PMC layers and of the hybrid interfaces.

3. In situ NDE/SHM

- Integrate SHM capabilities through networked sensor/actuator arrays, diagnostic algorithm development, control theory and fabrication process optimization.

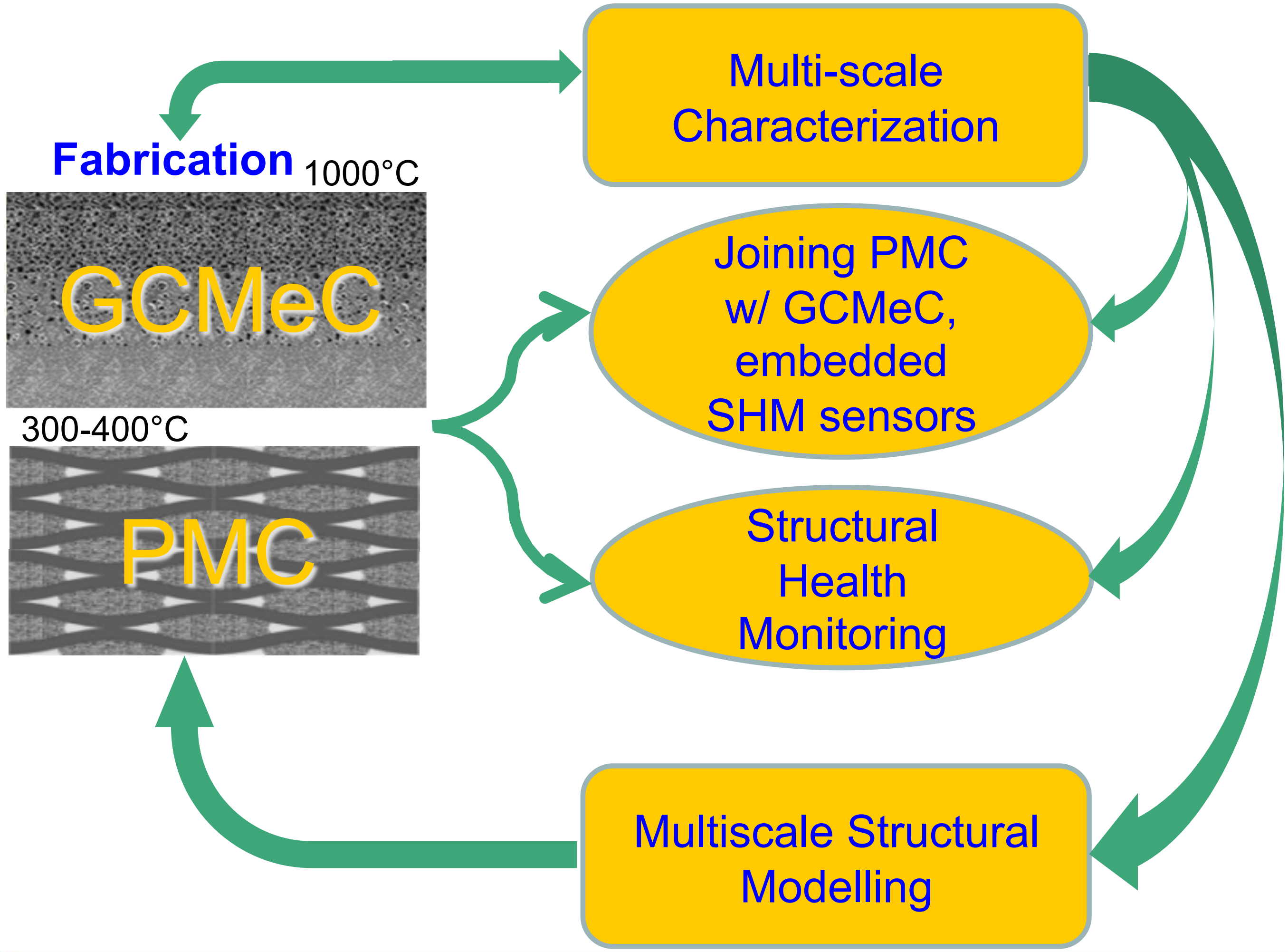
4. Multiscale Modeling

- Develop novel material systems for use in extreme environments: design FGHC microstructure, develop experiments and interpret data to obtain basic material properties.

Research Thrust Area Members

Fabrication	Characterization	NDE/SHM	Modeling
Karaman	**Sottos**	**Chang**	**Whitcomb**
Radovic	Radovic	Inman	Inman
Ounaies	Ounaies	Ounaies	Geubelle
Chang	Karaman	Seidel	Seidel
Lagoudas	Lagoudas	Lafdi	Lagoudas
White	Goulbourne	Goulbourne	Reddy
Lafdi	Lafdi		Ochoa
	Ochoa		Gao
			Cizmas

Functionally Graded Hybrid Composites (FGHCs) - The concept



- **Initial material parameters**
- **Validation experiments**

Functionally Graded Hybrid Composites (FGHCs) – The team

Fabrication of Graded Ceramic Metal Composites (GCMeCs)
Radovic (TAMU – Ceramics and MAX phases)
Karaman (TAMU – Ti alloys and SMAs)

Fabrication of Polymer Matrix Composites (PMCs)

Actively Cooled PMCs
White (UIUC)

High Temperature PMCs
Ounaies (TAMU)

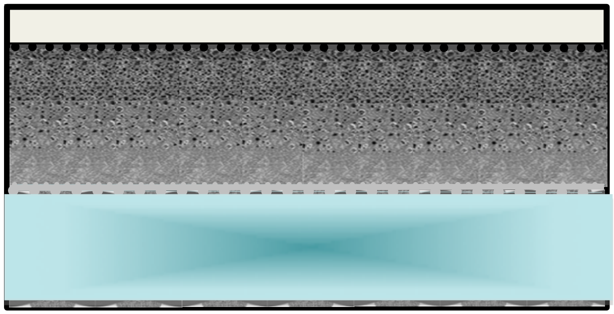
Joining of GCMeCs with PMCs
Ounaies, Radovic, Karaman (TAMU)
Lafdi (UDRI)

Embedding SHM modules and networks
Ounaies (TAMU) Inman (VTU)
Chang (Stanford)

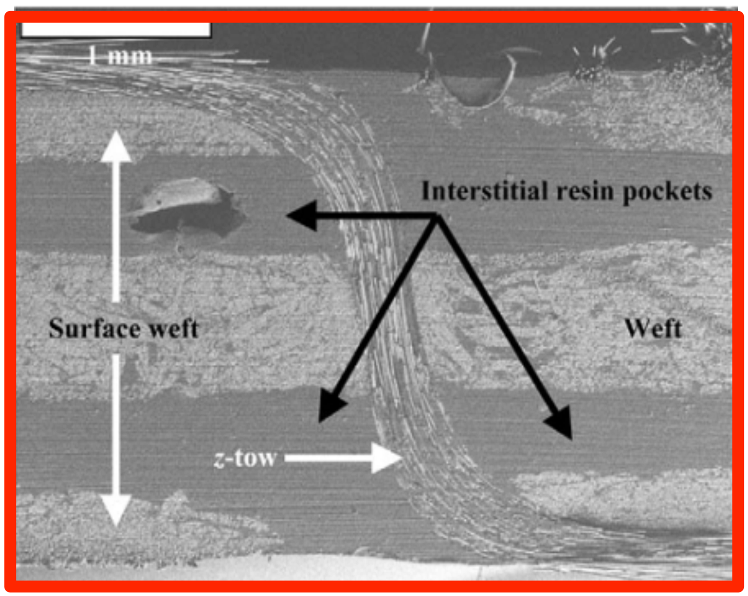
Research Thrust 1
Development and Fabrication GCMeC

- **MAX Phases:** unusual combination of properties typical of either ceramics or metals – high fracture toughness.
- **Self-healing** damaged protective ceramic surface.
- Infiltration of Ti based shape memory alloys (**SMAs**) into porous ceramic template to enhance energy absorption capabilities.

Actively-Cooled PMCs (AC-PMCs)



Actively cooled polymer matrix composite (AC-PMC) layer



3-D Woven Microvascular Composites

AC-PMC Concepts

- **Short term:** 2D planar array of embedded microchannels layered within a PMC

- **Long term:** 3D woven PMC architectures with integrated microvascular networks with sacrificial fibers co-mingled with reinforcement tows

High-Temperature Polyimide-Based Composites

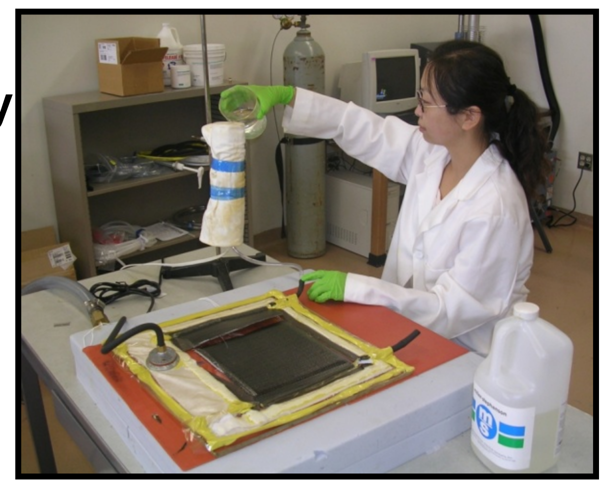
Polyimides have good thermo-oxidative stability, resistance to moisture absorption, relatively high moduli, and can withstand hot spikes up to two times their T_g.

HT-PMC Concepts

- Polyimides with T_g up to 400 ^{o}C (Maverick Co. and AFRL)
- Aromatic polyimides with varying dianhydrides

Depending on polymer viscosity

Solution-cast, Thermal Cure then Autoclave



Solvent-assisted Resin Transfer Molding

Research Thrust 1

Development and Fabrication Timeline

	6/09-9/09	10/09-1/10	2/10-5/10	6/10-9/10	10/10-1/11	2/11-5/11	6/11-9/11	10/11-1/12	2/12-5/12	Year 4	Year 5
Development of Functionally Graded Hybrid Composites (FGHCs) (Radovic, Karaman, Ounaies, White, Chang, Lafdi, Lagoudas)											
Functionally Graded Ceramic/Metal Composite (GCMeC) Layer						**O**			**E**		
Fabricate homogeneous metal infiltrated ceramic preforms	x	x	x	x							
Fabricate functionally graded metal and PZT infiltrated ceramics			x	x	x	x				x	
Self-Cooling Microvascular AC-PMC Layer							**O**			**E**	
Sacrificial fiber processing & network optimization	x	x	x	x	x	x					
Weave co-mingled tows for 3D preforms for microvascular composites			x	x	x	x	x	x	x	x	x
High-Temperature Polyimide-Based HT-PMC Layer				**O**				**E**			
Processing studies on BMI based polyimide	x	x	x	x	x	x	x		x	x	
Explore fuzzy glass and Sic fibers-fabric reinforcement				x	x	x	x	x	x	x	x
Incorporate self cooling concept									x	x	x
Joining GCMeC and PMC							**O**			**E**	
Grow CNTs (nano columns) on interfaces for bonding		x	x	x	x	x	x		x	x	x
Explore metal z-pinning as a joining technique		x	x	x	x	x		x	x	x	x

Research Thrust 2
Multiscale Characterization

Characterization of Composite Layers

- Graded Ceramic/Metal Matrix Composites
- Polymer/Matrix Composites
- Local Strain Fields/Damage Initiation

Interfaces and Bonded Joints

- Thermal Impedance
- Interfacial Delamination

Structural Performance

- Impact Response
- Vibration Analysis

Characterization Scales

nm

reinforcement/ matrix interface

µm

microvascular channels

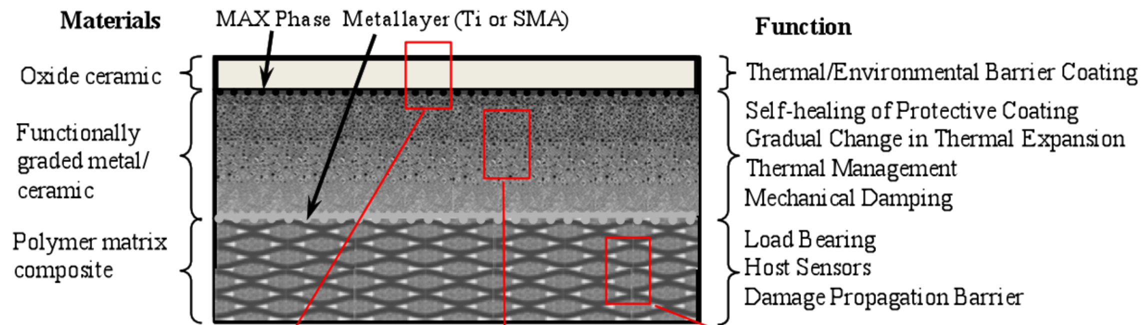
bonded interfaces

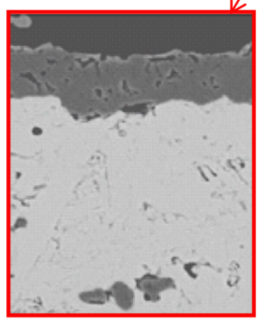
mm

composite layer properties

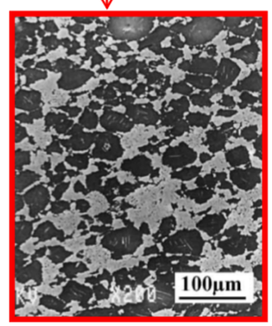
structural response

cm

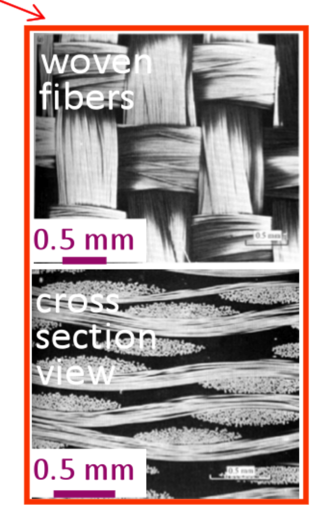




SEM micrograph of 15 µm thick protective Al_2O_3 surface layer formed after 10,000 heating cycles of Ti_2AlC [Ref]



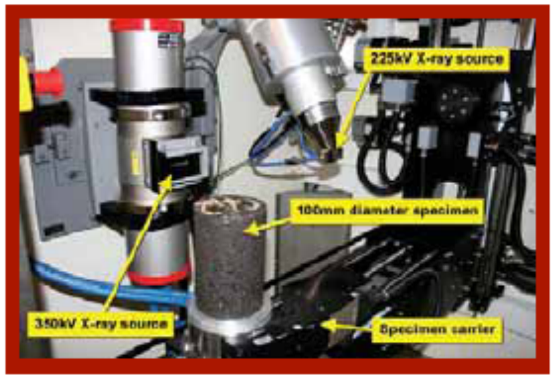
SEM of Ti_2AlC (light) + γTiAl (dark) as an example of MAX phase composite. [Ref]



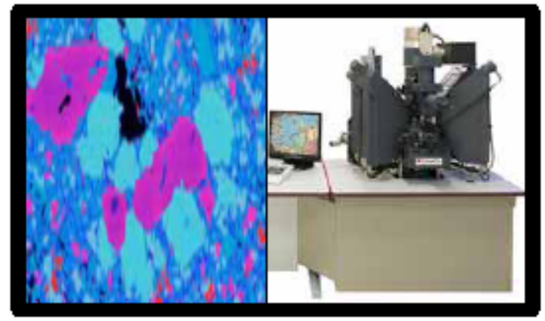
Structural Characterization of GCMeCs

High Temperature X-Ray Diffractometer (up to 1500K)

Micro CT for non-destructive characterization of metallic and ceramic phases and porosities

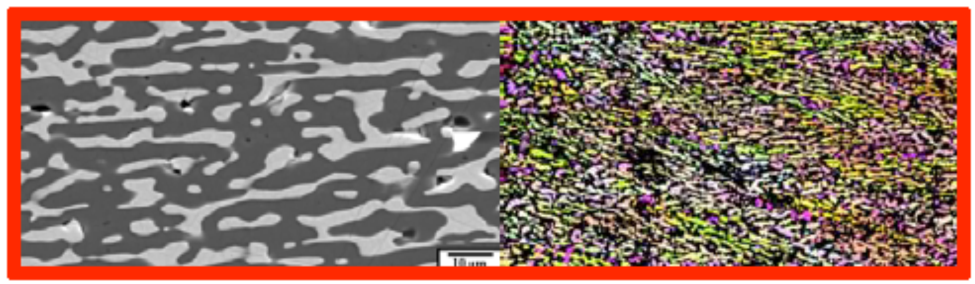


Electron Microprobe Analyzer and Wave Dispersive Spectroscopy (WDS) to study compositional variations across interfaces



Hermetic, beryllium dome high temp heating stage under 6x10^{-7} mBar vacuum

SEM and Orientation Imaging Microscopy (OIM) for phase morphology, distribution, and texture



Interfaces and Joints

- Characterize various bonding strategies and material configurations using both quasi-static and dynamic testing at varying length scales.

  bonding of metal

  - to consolidated composite using vertical nanocolumns followed by resin infusion.
  - to an intermediate fabric preform using vertical columns grown on both surfaces, with subsequent infusion of resin.
  - using Z-pinning technology.

- Evaluate the quality of the interface with thermal impedance measurements.
- Interfacial integrity of GCMeC/PMC through the double cantilever beam (DCB) and end notch flexure (ENF) test from 70 to 1000 °C.

Research Thrust 2

Multiscale Characterization Timeline

	6/09-9/09	10/09-1/10	2/10-5/10	6/10-9/10	10/10-1/11	2/11-5/11	6/11-9/11	10/11-1/12	2/12-5/12	Year 4	Year 5
Multiscale Characterization of FGHCs (Sottos, Goulbourne, Ochoa, Lafdi, Ounaies,Radovic, Karaman, Lagoudas)											
Obtain Physical and Mechanical Properties of GCMeC and PMC Layers				**O**				**E**			
Microstructure and reinforcement architecture interdependence	x	x	x	x	x	x	x	x	x		
Local stress analysis and damage initiation			x	x	x	x	x	x	x	x	x
Thermomechanical and thermo-oxidative capacity		x	x	x					x	x	x
Interfaces and Bonded Joints						**O**				**E**	
Evaluate GCMeC/PMC joint shear strength, delamination resistance				x	x	x	x	x	x	x	x
Characterize thermal impedance of FGHC joints						x	x	x	x	x	
Assess integrity of micro-vascular network, sensor arrays			x	x	x	x	x	x	x	x	x
Structural Performance							**O**				**E**
Impact response of PMC, GCMeC, FGHCs with SHM network					x	x	x	x	x	x	
Determine modulus and damping parameters of FGHCs							x	x	x	x	

Research Thrust 3

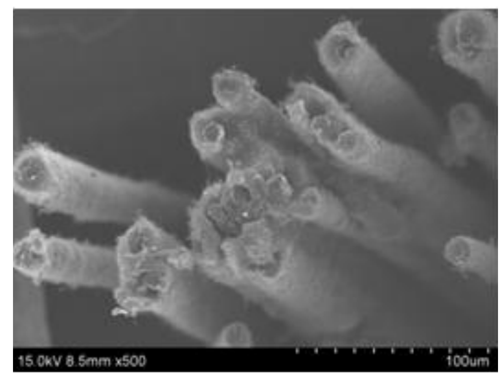
In situ NDE/SHM for Functionally Graded Hybrid Composites

- Develop a damage tolerant, reconfigurable multi-scale sensing network for monitoring the health state of the hybrid composite materials during manufacturing and in service.

- Investigate a series of algorithms that are sensitive to changes in impedance, to Lamb wave propagation, and to vibration signatures as the scale or type of damage changes.

Sensor Arrays

- A high-temperature piezoelectric sensor/ actuator.
- A sensor based on CNTs grown on fibers or fabrics.

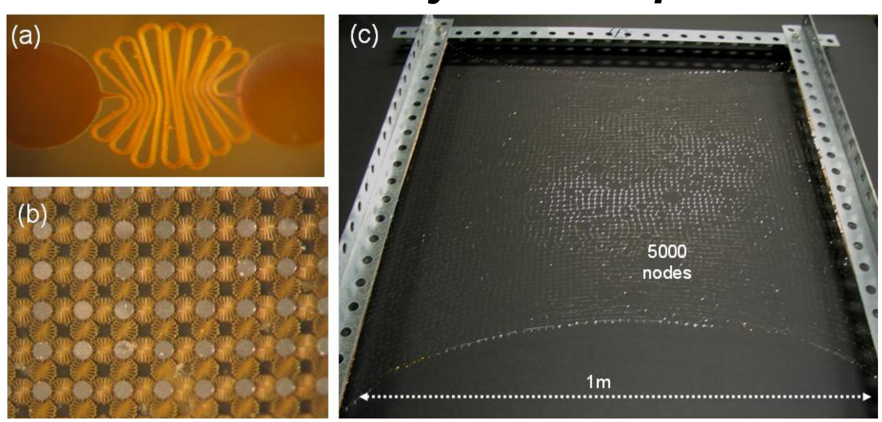


"Fuzzy fibers" where CNTs are grown on carbon fibers.

Sensory Network

- Develop an embedded sensory network to accommodate the sensor arrays providing communication among the sensors and collect data from them.
- The sensory network will consist of a flexible film with wires (micro- or nanoscale) connecting the sensors to each other and/or to a data interface.

The network will accommodate large arrays of sensors and actuators, and can be embedded within the hybrid composite.



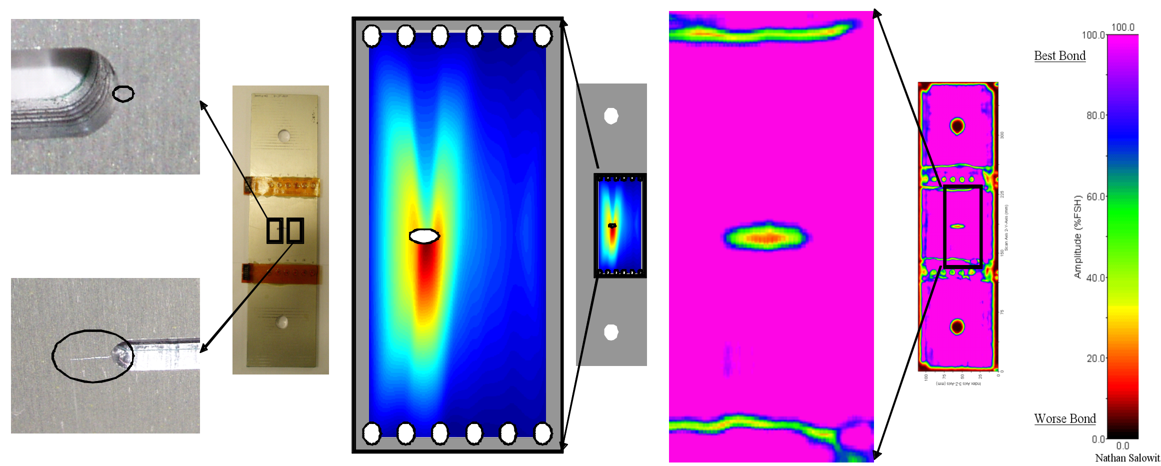
Expandable network made at Stanford University.

Diagnostics/Algorithm Development

Adapt algorithms to account for extreme temperature changes, methods to distinguish damage types, output only methods, baseline free methods, impact methods and networking.

Focus on impact force identification methods and develop a vibration based approach to determine the damage induced by impact.

Hybrid material with internal (Right) and externally (left) affixed PZT SMART layer networks.



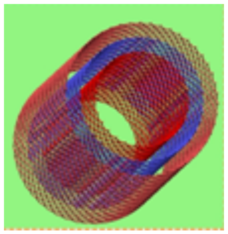
a) Hair line cracks detected by visual inspection on hybrid laminates, b) Diagnostic image by SHM detected the presence of these cracks, c) Traditional NDE.

Research Thrust 3
Insitu NDE/SHM Timeline

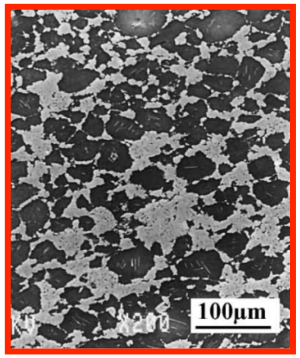
	6/09-9/09	10/09-1/10	2/10-5/10	6/10-9/10	10/10-1/11	2/11-5/11	6/11-9/11	10/11-1/12	2/12-5/12	Year 4	Year 5
In situ NDE/SHM for FGHCs (Chang, Inman,Lafdi, Ounaies,Goulbourne, Seidel)					**O**					**E**	
Fabricate polymer film sensor arrays with micro, nano ceramic PZT fillers	x	x	x	x	x	x	x	x			
Fabricate polymer films with aligned & dispersed CNTs for strain sensing		x	x	x	x	x	x	x	x		
Fabricate silicon carbide network to accommodate sensors arrays			x	x	x	x	x	x	x	x	
Develop diagnostics/algorithm		x	x	x	x	x	x	x	x	x	x

Research Thrust 4
Multiscale Modeling FGHCs and Joints

Fuzzy fiber



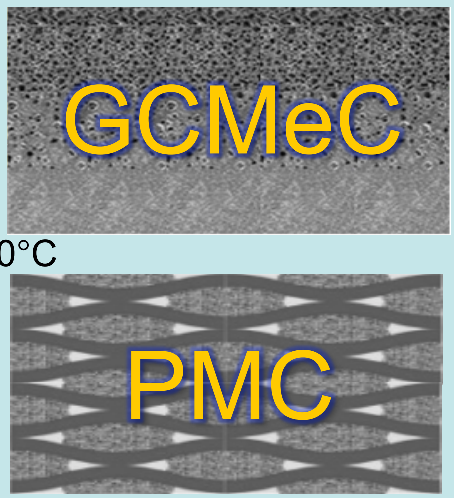
Seidel



Gao
Geubelle
Lagoudas
Whitcomb

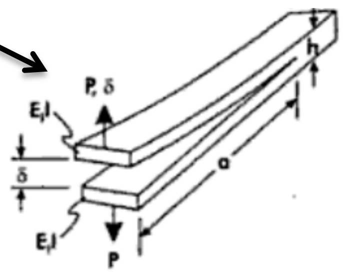
Cizmas

1000°C

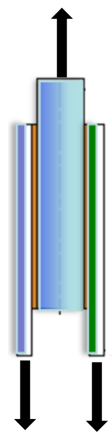


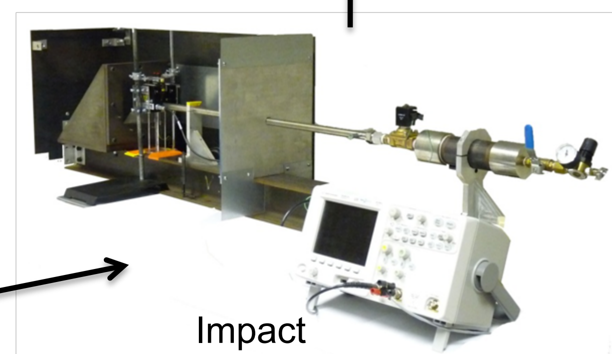
300-400°C

Optimize FGHC



Ochoa
Whitcomb

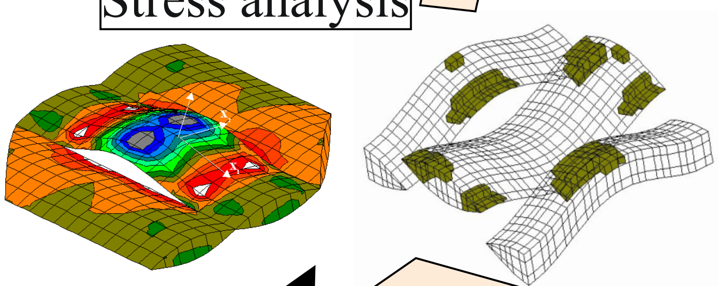




Reddy

Multiscale/Multifield Modeling of Damage

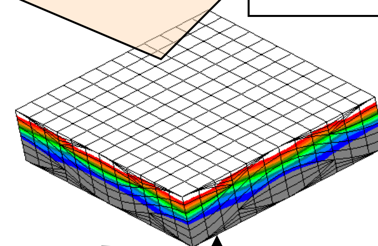
Stress analysis



Damage creates new pathways for diffusion

$$D_{ij} = D_{ij}(\Upsilon)$$

Oxidation/Diffusion analysis



$$\frac{\partial C}{\partial t} + \frac{\partial}{\partial X_i} J_i + R = 0$$

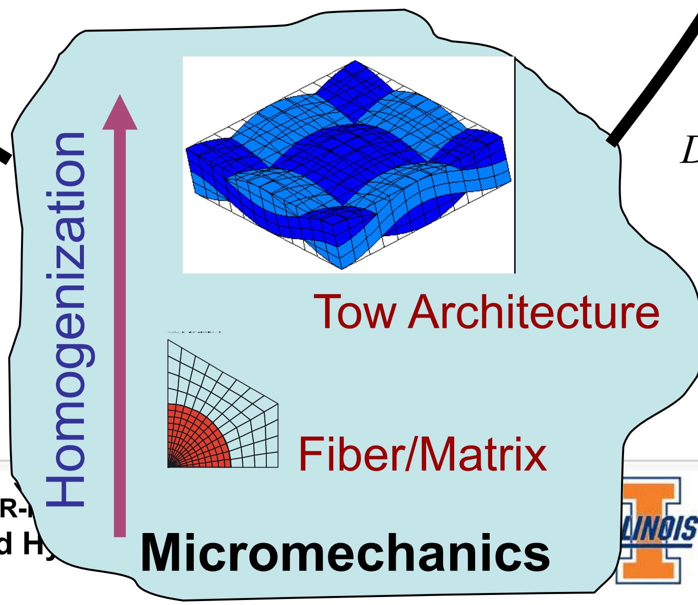
$$R = \left(\frac{\phi - \phi_{ox}}{1-\phi_{ox}}\right) R_0(T) f(C)$$

$$C_{ij} = C_{ij}(\phi)$$

Degrade mechanical properties

$$\phi = \min\left\{\phi_{ox}, \left(1 - \int_0^t \alpha(\varsigma) R(\varsigma) d\varsigma\right)\right\}$$

$$D_{ij}^{\ *} = \left\langle D_{ij}\right\rangle_{un}\left(\frac{\phi - \phi_{ox}}{1-\phi_{ox}}\right) + \left\langle D_{ij}\right\rangle_{ox}\left(\frac{1-\phi}{1-\phi_{ox}}\right)$$



… also, heat transfer

Structural Performance

Impact Behavior of Plate and Shell FGHC Structures

- Development of an efficient computational framework for use in the performance evaluation of the proposed FGHC, including bonded joints and functionally graded plate and shell type structural components subjected to low velocity impact.
- Finite element formulations based on traditional shear deformation shell theories as well as layer-wise theories will be developed with an elastic-plastic constitutive law based on a multiplicative decomposition of the deformation gradient.

Aeroelastic Model of FGHC Structural Response

- A flow solver based on Reynolds-averaged Navier-Stokes equations with a shear stress transport turbulence model will be used to predict the aerodynamic loads on a FGHC structure.
- The modeling effort will also capture two of the most common sources of structural nonlinearities: (i) geometric structural nonlinearities, and (ii) internal structural damping.

Research Thrust 4
Multiscale Modeling Timeline

	6/09-9/09	10/09-1/10	2/10-5/10	6/10-9/10	10/10-1/11	2/11-5/11	6/11-9/11	10/11-1/12	2/12-5/12		Year 4	Year 5
Multiscale Modeling FGHCs and Joints (Whitcomb, Reddy, Cizmas, Gao, Lagoudas, Seidel, Geubelle, Inman, Ochoa)												
Design of Material Architectures					**O**				**E**			
Micromechanics based modeling of GCMeC	x	x	x	x	x							
Multiscale optimization of AC-PMC and HT-PMC	x	x	x	x	x	x	x	x	x		x	x
Modeling of progressive damage in complex microstructures		x	x	x	x	x	x	x	x		x	x
Multiscale modeling of nanocomposites-based SHM	x	x	x	x	x	x	x	x	x		x	x
Impact behavior of plate and shell FGHC structures				x	x	x	x	x	x		x	x
Aeroelastic modeling of FGHC structural response	x	x	x	x				x	x		x	

Synthesis, Characterization and Prognostic Modeling of Functionally Graded Hybrid Composites for Extreme Environments

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Multi-scale Characterization

Joining PMC w/ GCMeC, embedded SHM sensors

Structural Health Monitoring

Multiscale Structural Modelling